Workmanship Risks: Reworking Printed Circuit Board (PCB) Solder Joints

Understanding and managing risks associated with underfilled through-hole solder joints

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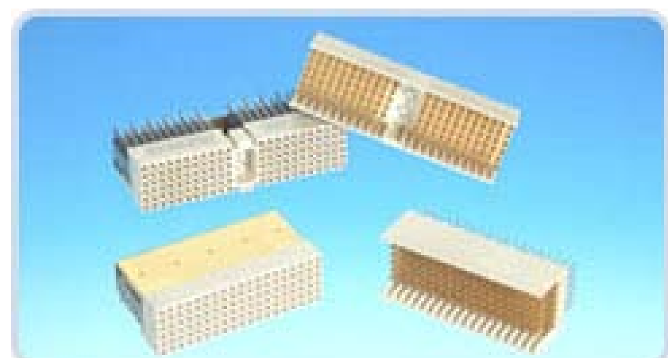
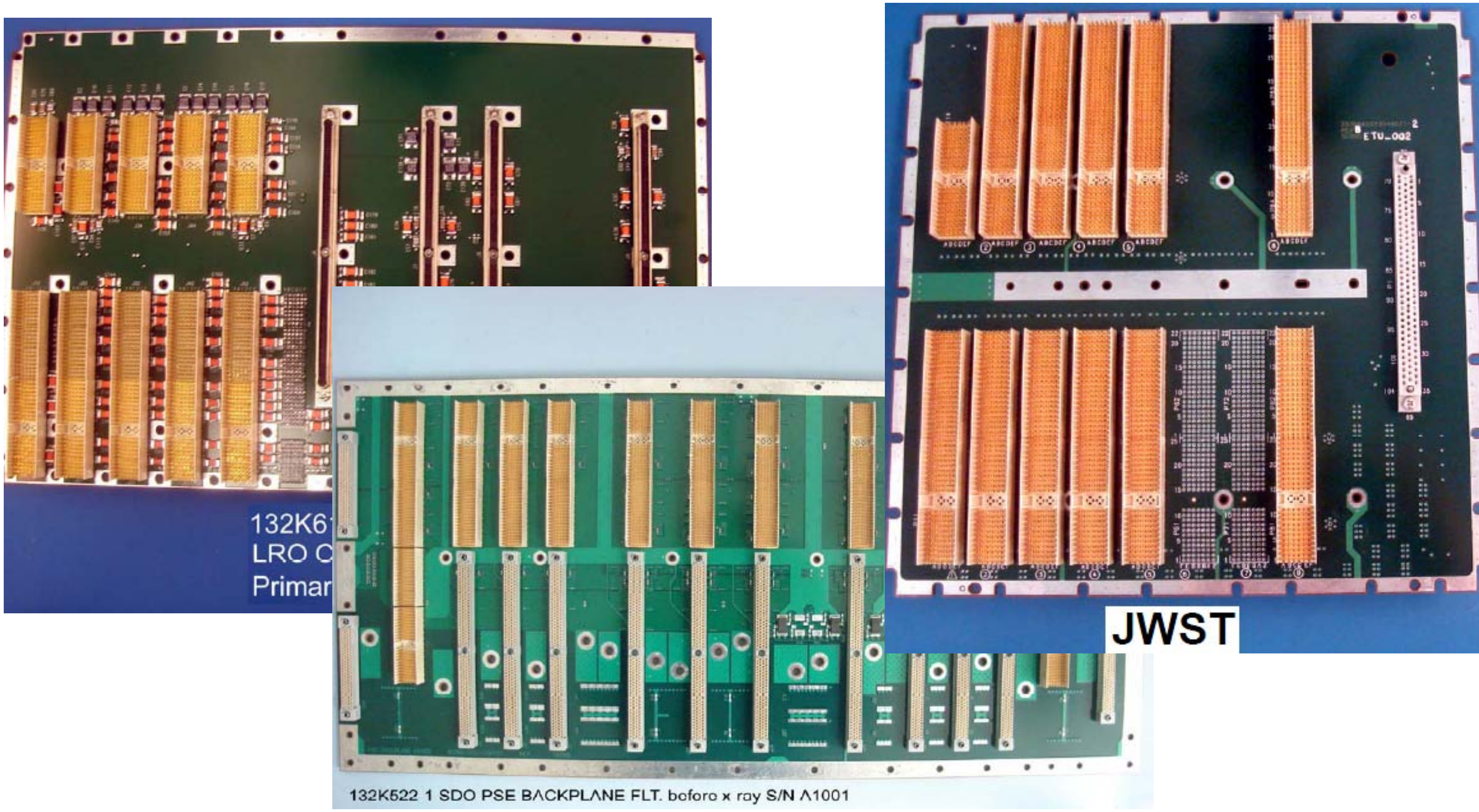
October 18, 2011

cPCI Solder Joints Routinely Found Underfilled

- cPCI style connector becoming standard for NASA backplanes
- Hypertronics brand is required to provide non-fretting contacts and solder tails. Commercial version is a reliability concern: uses tuning fork pin/socket contacts and press-fit board-side contacts.
- Backplane boards are becoming thicker and have increasingly higher percentages of copper (12 layers and counting)
- Soldering is performed by wave soldering machine or by hand.
- The typical model used has 100+ pins. Stand-off is 0.50 mm.



Courtesy: Hypertronics Corporation



Pin #	--	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1
Signal Name	**Row Z**	GND	GND	GND	GND	GND	GND	GND	GND	GND	GND	GND				GND	GND	GND	GND	GND	GND	GND	GND	GND	GND	GND
Signal Name	**Row A**	5V	AD[1]	3.3V	AD[7]	3.3V	AD[12]	3.3V	SERR#	3.3V	DEV SEL#	3.3V				AD[18]	AD[21]	C/BE[3]#	AD[26]	AD[30]	REQ#	BRSVP 1A5	BRSVP 1A4	INTA#	TCK	5V
Signal Name	**Row B**	REQ64#	5V	AD[4]	GND	AD[9]	GND	AD[15]	GND	SDONE	GND	FRAME#				AD[17]	GND	IDSEL	GND	AD[29]	GND	BRSVP 1B5	GND	INTB#	5V	-12V
Signal Name	**Row C**	ENUM#	V(I/O)	AD[3]	3.3V	AD[8]	V(I/O)	AD[14]	3.3V	SBO#	V(I/O)	IRDY#	*KEY*	*KEY*	*KEY*	AD[16]	3.3V	AD[23]	V(I/O)	AD[28]	3.3V	RST#	V{I/O}	INTC#	TMS	TRST#
Signal Name	**Row D**	3.3V	AD[0]	5V	AD[6]	M66EN	AD[11]	GND	PAR	GND	STOP#	GND				GND	AD[20]	GND	AD[25]	GND	CLK	GND	INTP	5V	TDO	+12V
Signal Name	**Row E**	5V	ACK64#	AD[2]	AD[5]	C/BE[0]#	AD[10]	AD[13]	C/BE[1]#	PERR#	LOCK#	TRDY#				C/BE[2]#	AD[19]	AD[22]	AD[24]	AD[27]	AD[31]	GNT#	INTS	INTD#	TDI	5V
Signal Name	**Row F**	GND	GND	GND	GND	GND	GND	GND	GND	GND	GND	GND				GND	GND	GND	GND	GND	GND	GND	GND	GND	GND	GND

The Quality Policy: NASA

Solder fill requirement for through-hole solder joints is intended for leaded parts whose solder joints are readily viewable:

NASA-STD-8739.3, para. 11.2.3

- Heat may be applied to either side
- No bulk solder defects (cracks, blow-holes, excessive graininess)
- Solder quantity shall exhibit:
    - flow through to opposite side
    - bonding of lead to solder pad but not necessarily wetting to entire periphery of pad
    - slight shrink back is acceptable

NASA-STD-8739.3, para. 4.3.2.d and 8.4.1

Parts mounting design requirements shall allow full visual or nondestructive inspection of all soldered connections.

Does not say: “fully filled” or “100% filled”

The Quality Policy: (Soon to be NASA) J-STD-001ES

J001E Reference	Space Applications Requirement (as changed by this Addendum)
6.2.2	Through-Hole Component Lead Soldering. When soldering component leads into PTH connections, the goal of the process is to accomplish 100% fill of the PTH with solder and good wetting to the lands, lead, and barrel top and bottom. The solder connection **shall meet the requirements of Table 6–4 of this addendum**, regardless of the soldering process, e.g. hand soldering, wave soldering, intrusive soldering, etc.

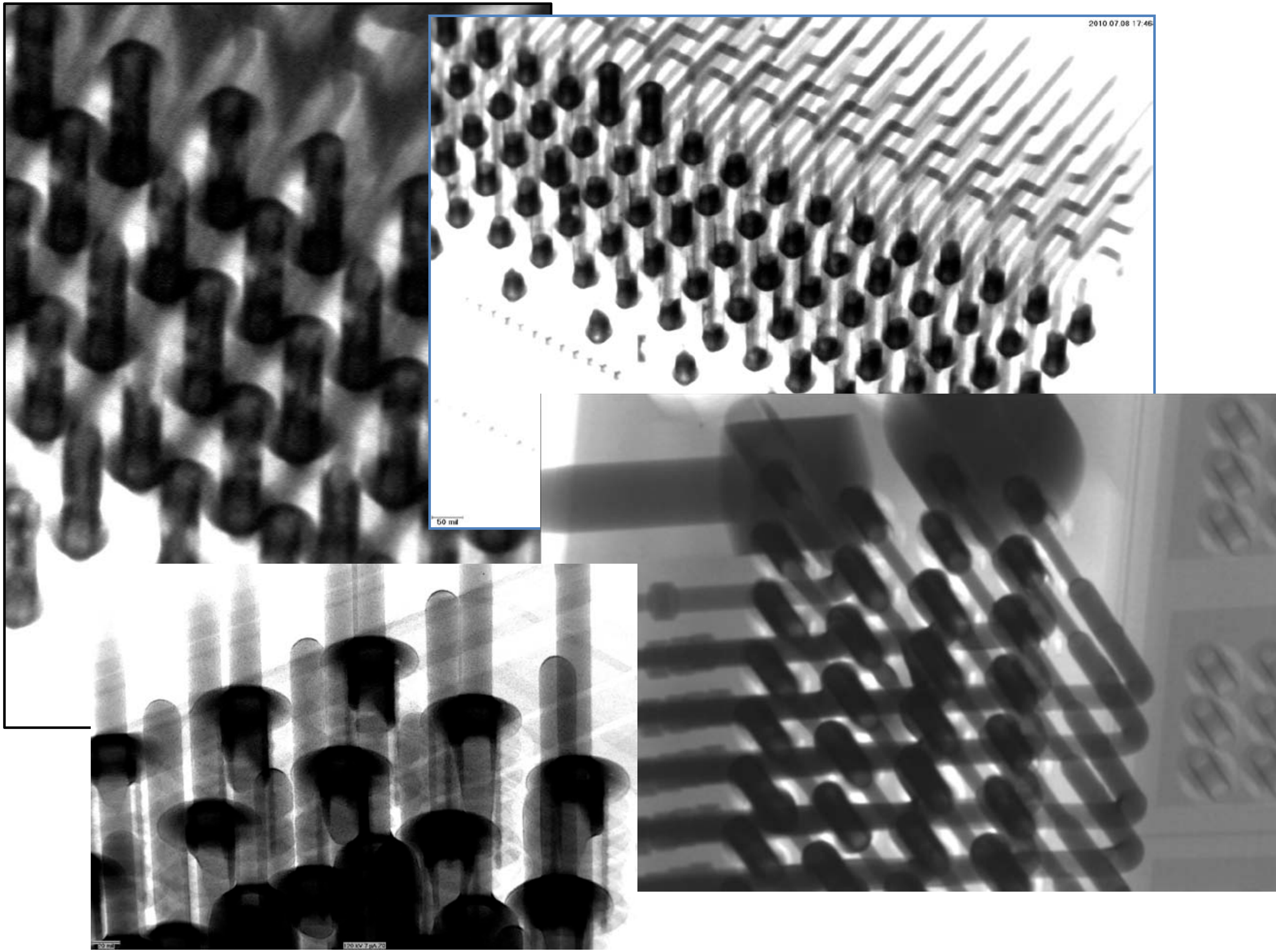
Table 6–4 Supported Holes with Component Leads, Minimum Acceptable Conditions[1]

A. Vertical fill of solder.[2,3]	75%
B. Circumferential wetting of lead and barrel on solder destination side.	360º
C. Percentage of original land area covered with wetted solder on solder destination side.[3]	0
D. Circumferential fillet and wetting of lead and barrel on solder source side.	360º
E. Percentage of original land area covered with wetted solder on solder source side.[3]	75%

Note 1. Wetted solder refers to solder applied by any solder process including intrusive soldering.
Note 2. Applies to any side to which solder or solder paste was applied. The 25% unfilled height includes a sum of both source and destination side depressions.
Note 3. Provided the solder has flowed onto, and wetted to, the lead and solder land before receding.

IPC does not speak to artifacts that require X-ray inspection to view, such as buried voids or underfill.

Can't see this for Hypertronics cPCI solder joints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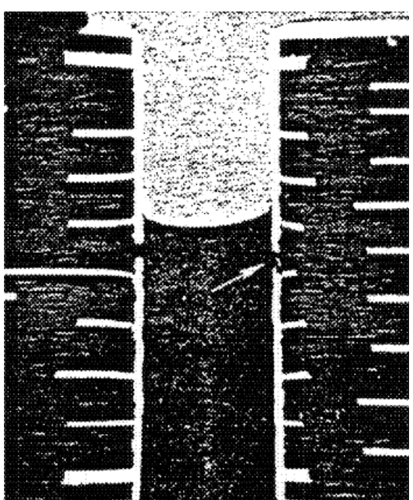
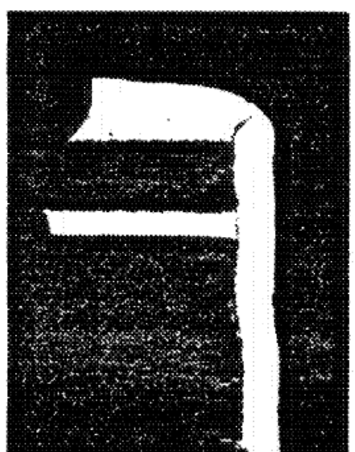
50 mil

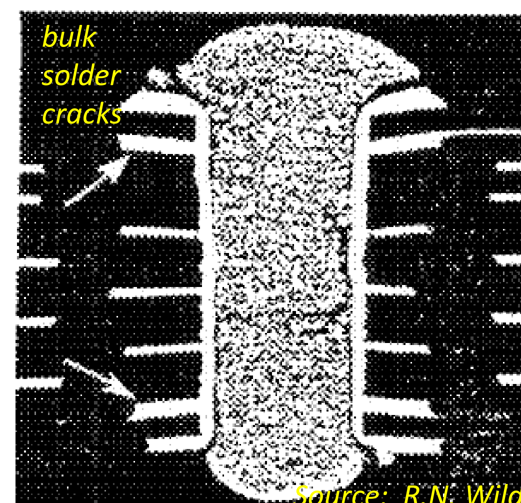
What are the failure modes that we are trying to prevent? *Electrical "open" or unacceptable increase in connection resistance.*

What causes this change in electrical connectivity?

- full or nearly full disconnection with the device lead.
- full or nearly full disconnection between solder and barrel wall and solder pad
- lack of solder + 360° barrel crack isolates PCB layers from lower/upper layers.
- barrel crack or trace crack separates trace from the barrel.



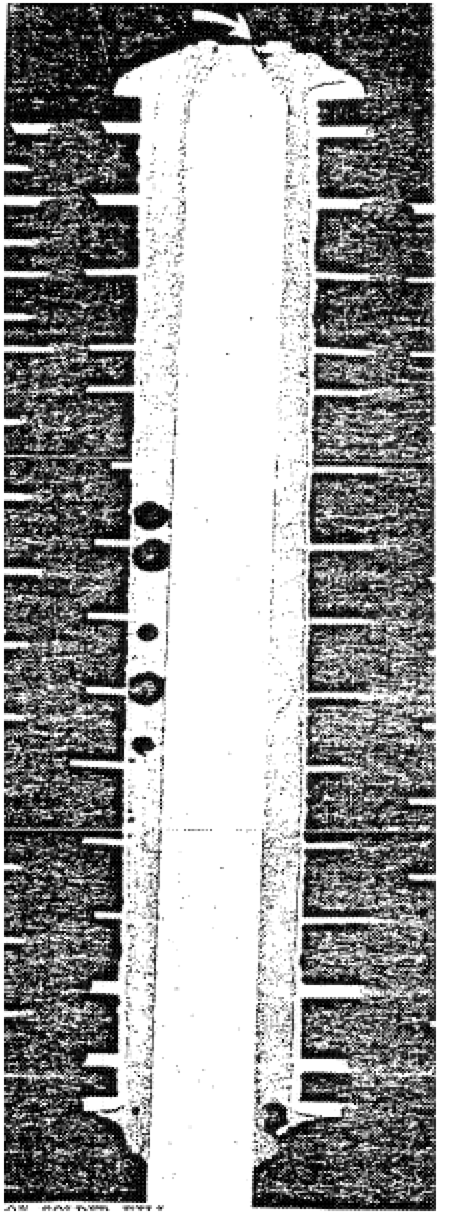




Missing or disconnected solder doesn't always result in electrical failure for this solder joint type because the barrel/solder configuration is highly redundant.

The most non-redundant part of the interconnect is between the trace and barrel.

Solder and barrel/trace failures often go undetected at room temperature and are detected at high temperature during testing.



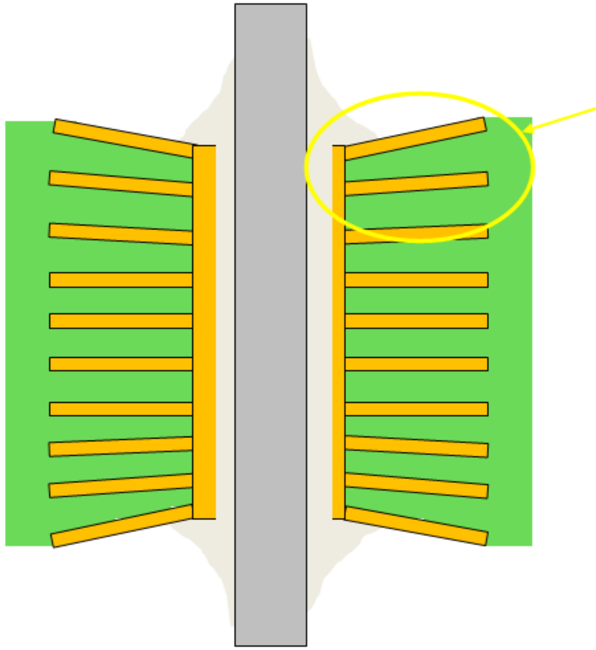
Will an underfilled through-hole joint have a shorter trip to failure than a fully filled joint?

How will it tend to fail?

If fully filled joints last longer, should we try to fix underfilled joints with rework?

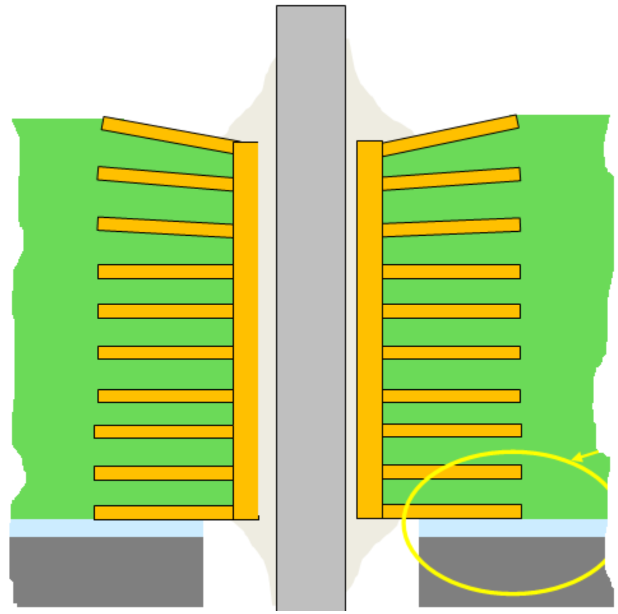
1. Lea, Colin. “Evidence that Visual Inspection Criteria for Soldered Joints are No Indication of Reliability”, *Soldering and Surface Mount Technology*, 1991, vol. 3, issue 3, pp19-24.
2. Lea, Colin. “The Effect of Blowholes in Soldered PTH Assemblies”
3. Lea, Colin. “The Harmfulness of Re-Working Cosmetically Defective Solder Joints”:
4. Keller, J; Waszczak, J. “The Case for Unfilled PTHs,” *Electronics Packaging and Production*, 1973, vol. 13, issue 10, pp144-149
5. Wild, R.N.; “Thermal Characterization of Multilayer Interconnection Boards,” The Institute of Printed Circuits Conference, Orlando, FL, April 1977.
6. Garrison, Ann; Lee, Mike; Park, Hyun; and Todd, Norma Lee. “How Much is too Much?: The Effects of Solder Joint Rework on Plated-Through Holes in Multilayer Printed Wiring Boards”, 1994
7. Electronics Manufacturing Productivity Facility. “Tri-Service Evaluation of Field Electronic Hardware,” June 1990

R. N. Wild



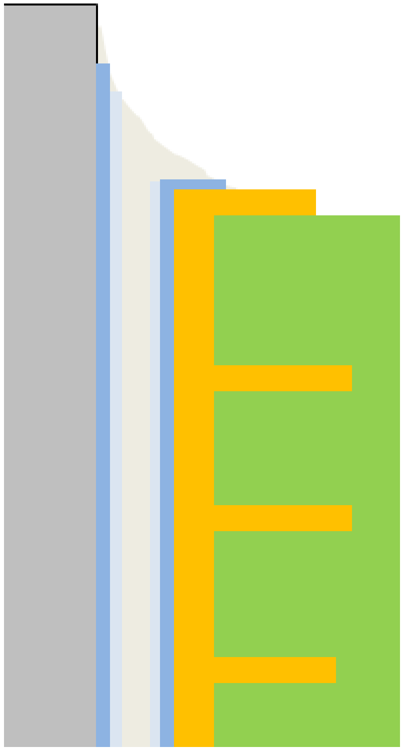
Z-axis expansion of the dielectric layers during exposure to soldering heat will deform and stress outer barrel-to-trace connections.

R. N. Wild



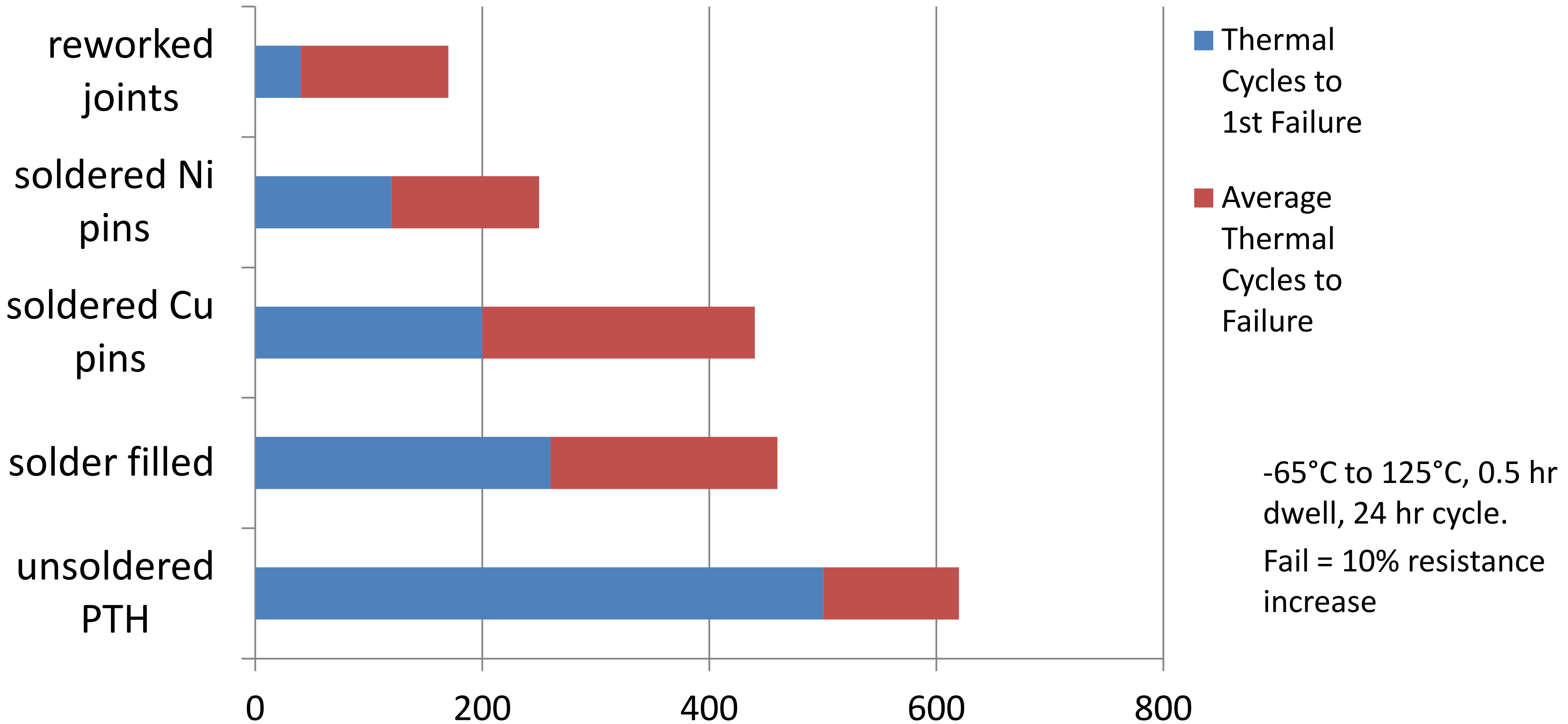
Attachment of the board to a metal frame transfers all Z-axis expansion to one size of the PCB increasing stresses there.

Colin Lea



Solder cracking starts near intermetallic layers which are strong but less ductile. Bulk solder near intermetallic layer will not have the same Sn-Pb microstructure as the rest of the joint.

Wild, R.N.; “Thermal Characterization of Multilayer Interconnection Boards – Phase II,” The Institute of Printed Circuits Conference, Orlando, FL, April 1977.



All soldering reduced PTH barrel life.

Not all “fully filled” joints are equal. Reworked joints (3 heats) have less than half the life expectancy of an first-time fully filled solder joint. Wild’s cycles-to-1st failure is in the infant mortal range.

Wild, R.N.; “Effect of Backpanel PTH Solder Fill in Life Testing Environment,” 1981.

Three board thicknesses tested: 0140”, 0.118”, 0.200”
Connector types: 50 – 225 pins, 1” – 7.5” long; barrels masked with oxide to control solder wetting depth
Fill levels: 0% (capped), 15%, 25%, 50%, 75%, 100%
Wave and hand soldered.

-55°C to 105°C, 1 hr dwell, 3 hr cycle

Results:

0.140” board: capped joints failed between 200 and 260 cycles, No Other Failures
0.118” board: one 15% joint failed between 240 and 400 cycles, No Other Failures (even 0%)
0.200” board: capped joints failed at 50 cycles, No Other Failures

Cracking at top pad was common and related to additional stress on the joint from the “moving” connector
No difference between cycles-to-failure for hand-soldered vs wave soldered connectors.

Keller, J; Waszczak, J. "The Case for Unfilled PTHs," *Electronics Packaging and Production*, 1973, vol. 13, issue 10, pp144-149

Jeannette paraphrases:

Often you cannot inspect PTH solder fill on the component side: recognizes IPC requirement which cannot be achieved with many connectors.

If you have accepted the PCB lot, why not rely on a single end of a through-hole solder joint which is electrically the same node as the second side as well as the internal barrel surface?

Lea, Colin. "Evidence that Visual Inspection Criteria for Soldered Joints are No Indication of Reliability", *Soldering and Surface Mount Technology*, 1991, vol. 3, issue 3, pp19-24.

Tested the theory that "the relationship between the [solder] joint appearance or its physical characteristics and its service reliability is known"

Used pits and voids as a test case because they were often reworked and their origins are so well understood that they could be made on-demand. Samples were 25% to 100% full volume (not "underfilled" because loss of solder was by voiding).

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None of the solder failed in tensile testing. Only the wire or the solder pad broke.

Results of Thermal Shock Testing and Low Cycle Thermal Fatigue			
Solder Volume (mm$^{3)}$	Type of “defect”	Visual appearance	Thermal shock performance
1.0 (full)	None	BEST	WORST
> 0.9	Blowholes & voids	↑	↑
0.7 – 0.9	Blowholes & voids	↑	↑
< 0.7	Blowholes & voids		
< 0.6	Blowout (underfill)	WORST	BEST

Lea, Colin. "The Harmfulness of Reworking Cosmetically Defective Solder Joints", *Soldering and Surface Mount Technology*, 1990, No. 5, pp4-9.

Researched a manufacturer's product that was replaced and returned by users to manufacturer when there was a failure. Touched-up joints were marked before original shipment. Failures in returned units correlated to touched up joints.

Hand soldering can produce higher levels of intermetallic compound than wave soldering.

Reworking tends to add more solder to the fillet which is less compliant than a "slim" fillet.

Soldering time during rework correlated to lower thermal cycle life.

Would like to have data for:
Reliability of original *(Not Reworked)* fully filled joint vs underfilled original joint
Reliability of reworked joint vs underfilled original joint
Solder using representative methods: hand soldering and wave soldering

If X-ray inspection is needed, what must we look for as a defect?

Evaluation to Learn Best Response When we Find Underfilled cPCI Joints

Determine:

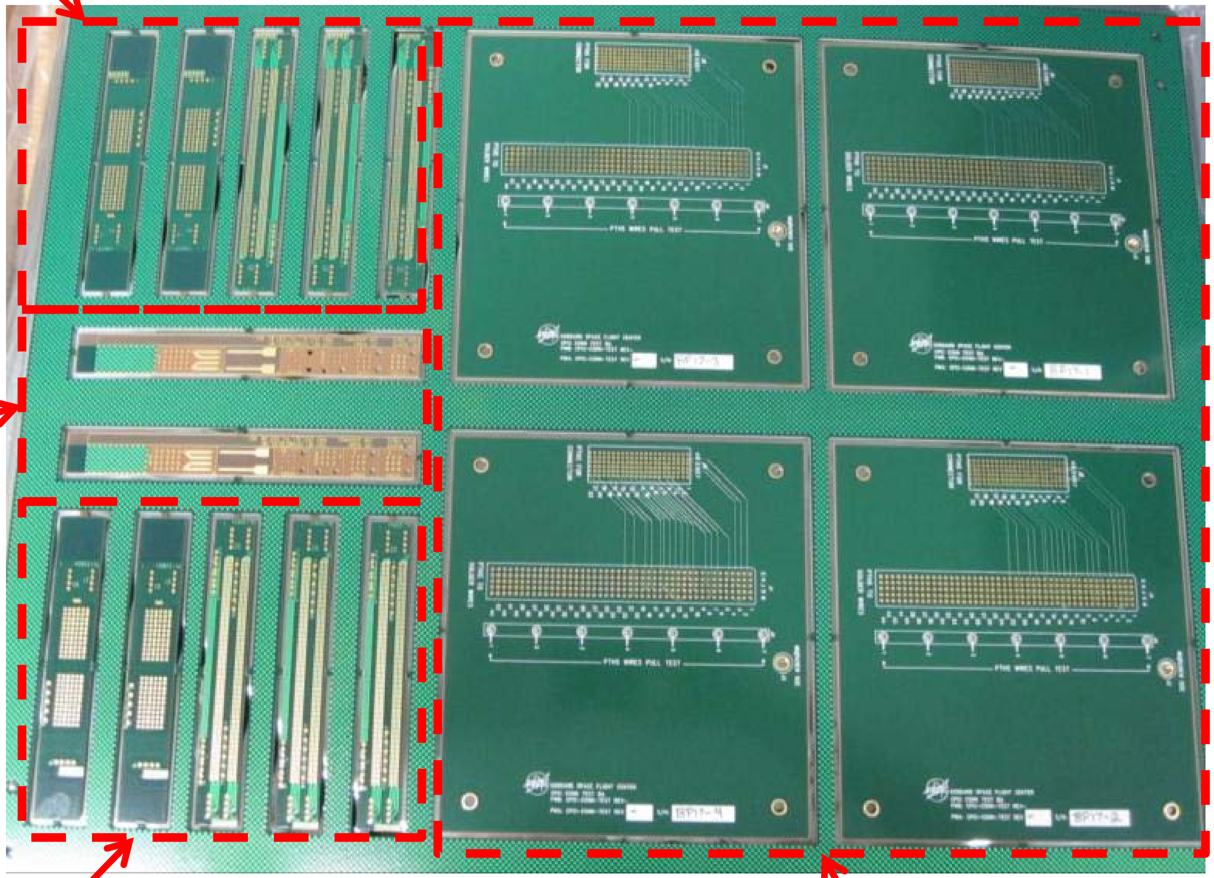
- Minimum amount of solder fill required for a reliable joint (from lead to PCB trace)
- Operating conditions which enable under-filled joints to pass generic “space grade” reliability requirements
- Impact of location of voids and solder
- Solder fill and voiding content impact on PWB reliability
- How reheating cycles from soldering (touch-ups or intentional rework) reduce the reliability of joints
  - with or without voiding
  - with or without 100% fill

Four Separate Tests

- Wire Pull Testing
  - How much force is required to pull out an entire connector? How would this compare to forces normally experienced by these connectors?
- Thermal Cycling
  - How reliable are under-filled solder joints compared to fully filled solder joints?
- Capacitance Testing
  - How much stress does the board accumulate from under-filled solder joints compared to 100%-filled solder joints and re-worked solder joints?
- Interconnect Stress Testing
  - How much stress does the board experience from thermal cycling due to under-filled and reworked solder joints?

Panels

Coupons for IST



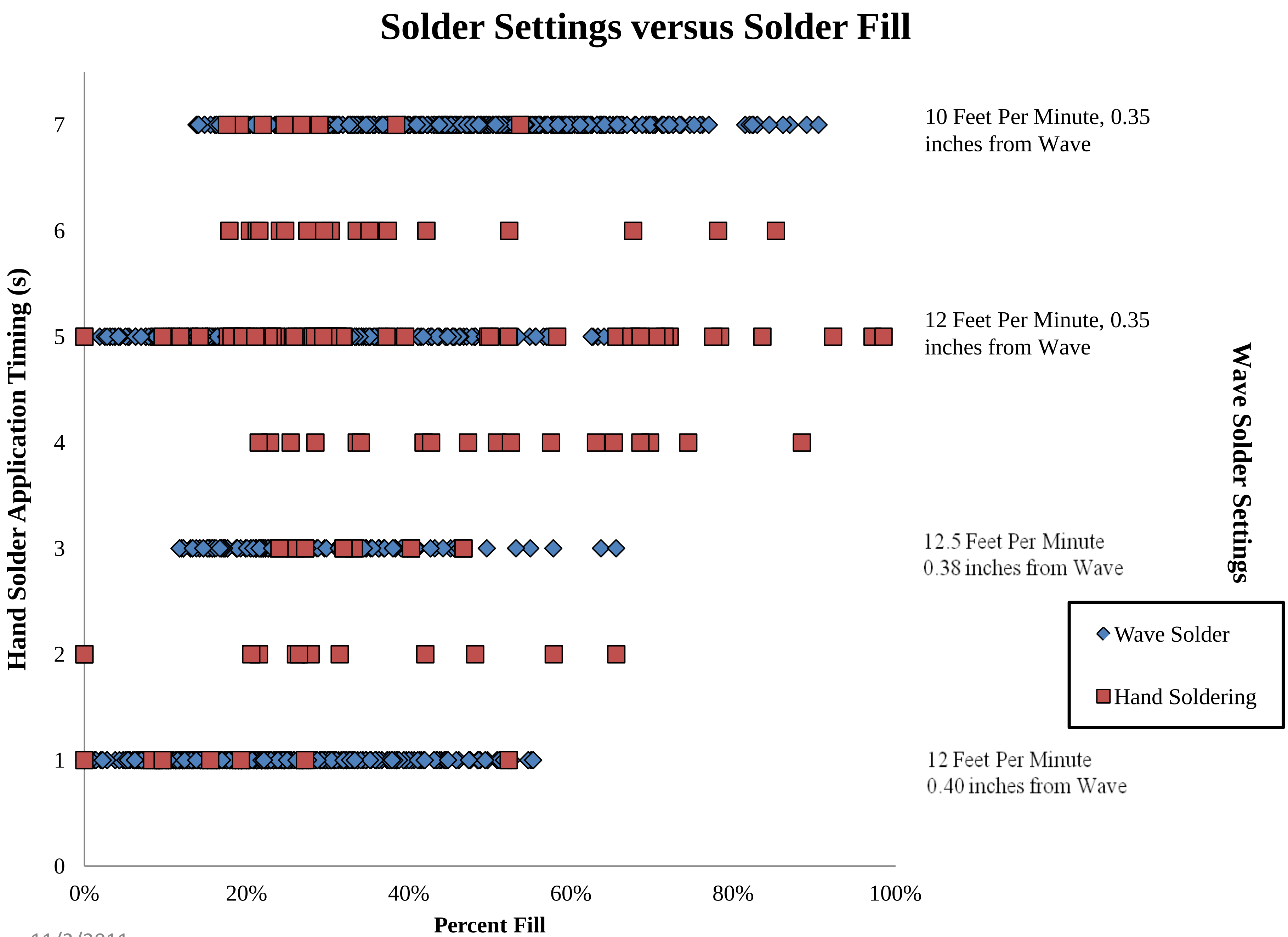
Cross-Section Coupons for Code 300

Coupons for IST

Boards (4) for Thermal Cycling and Wire Pull Tests

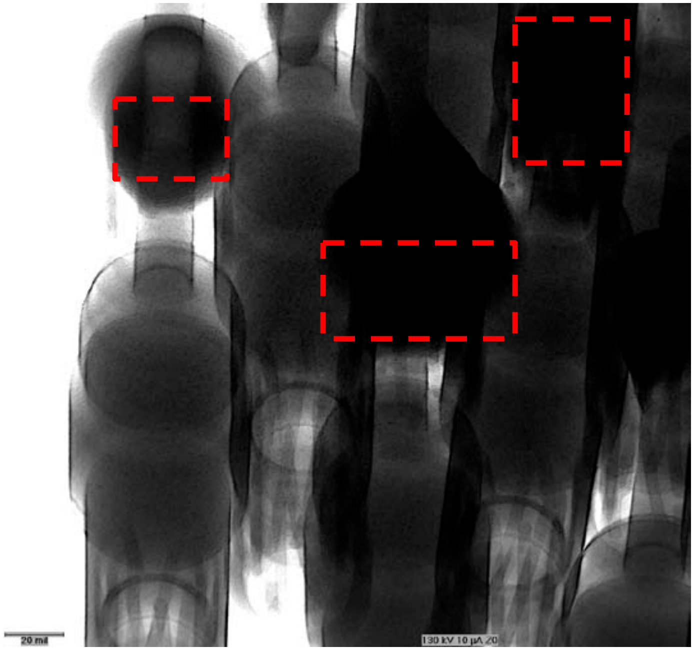
Assembly

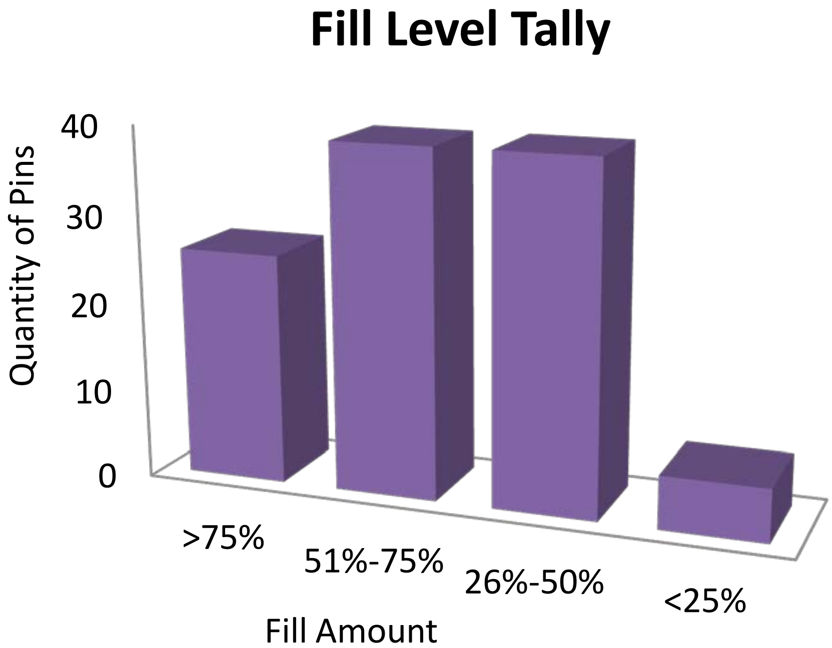
- Bake out boards for 24 hours to remove moisture
- Reflow boards to simulate surface mount component assembly (cPCI connectors are installed last)
- Developed method of hand soldering for consistent fill amounts
  - Small gauge tin-lead solder wire
  - Larger sized solder tip
  - 300˚C soldering iron
  - Vary time of solder application
    - 100% fill: 5 seconds
    - 30-50% fill: 2-3 seconds
    - Less than 30% fill: 1 second
  - Visits to BAE Systems in Manassas, VA to learn sample prep techniques
  - Practice
- Wave soldering performed at GSFC subcontractor
  - Preheat boards
  - Time solder wave


Solder Settings versus Solder Fill
Hand Solder Application Timing (s)
0
1
2
3
4
5
6
7
0%
20%
40%
60%
80%
100%
Percent Fill
10 Feet Per Minute, 0.35 inches from Wave
12 Feet Per Minute, 0.35 inches from Wave
12.5 Feet Per Minute 0.38 inches from Wave
12 Feet Per Minute 0.40 inches from Wave
Wave Solder Settings
Wave Solder
Hand Soldering

Fill Calculation

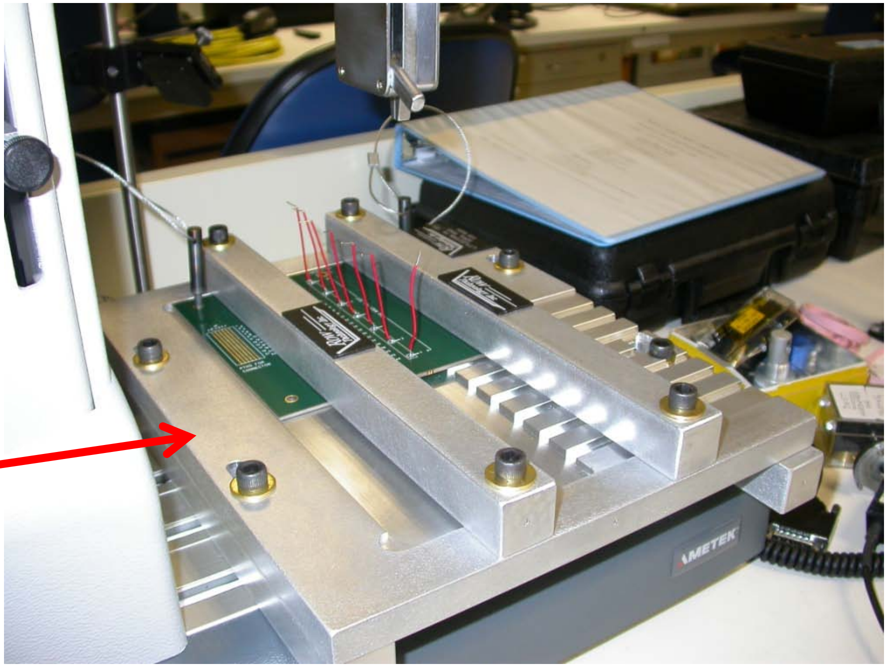
- Record quantity of solder in grams
- Examine using X-Ray
  - Calculate fill using photos – pixel count





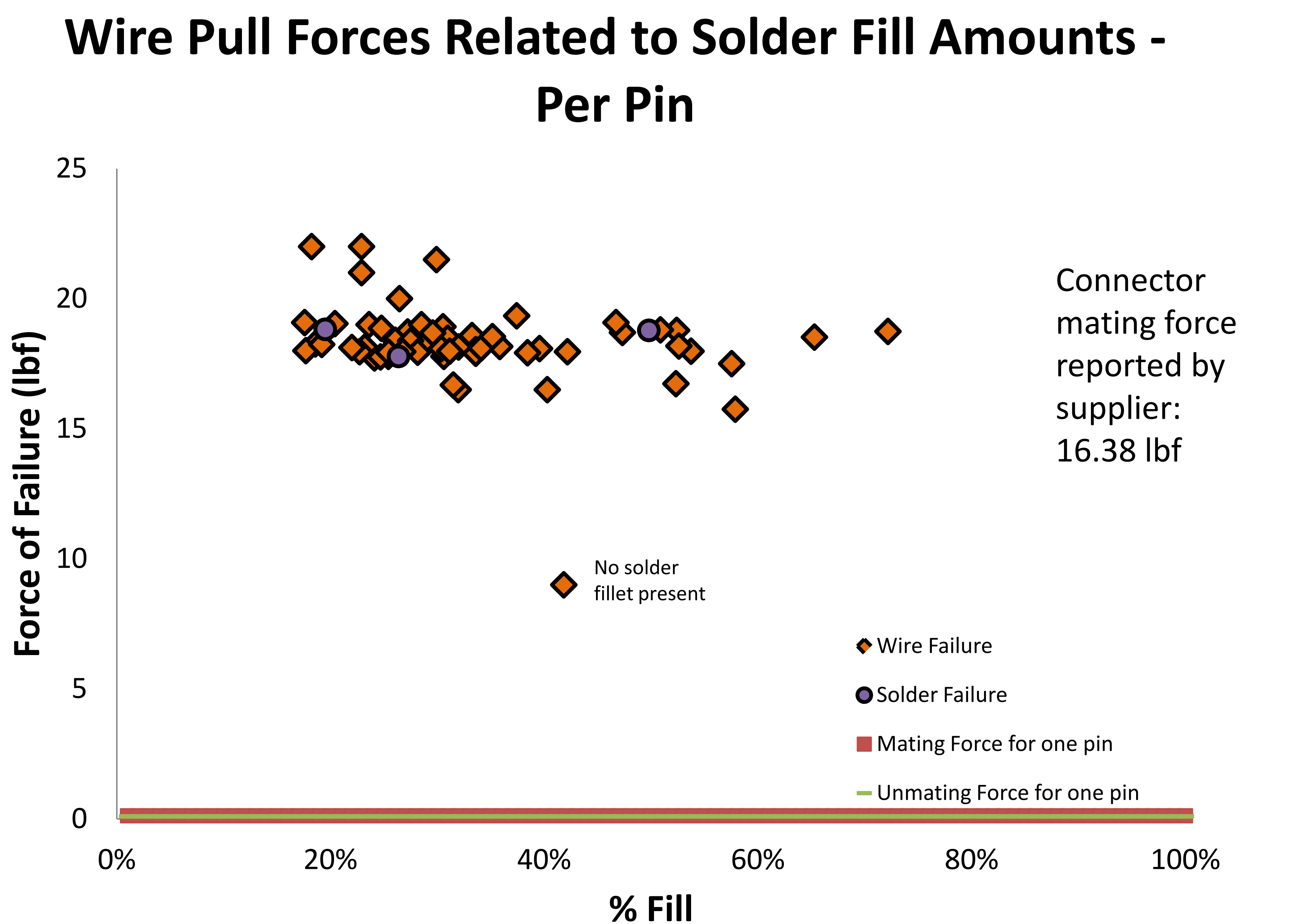
Wire Pull Test Setup

- Chatillon TCD225 Force Tester with 200lb load cell
- Custom fixture designed by Chatillon supplier

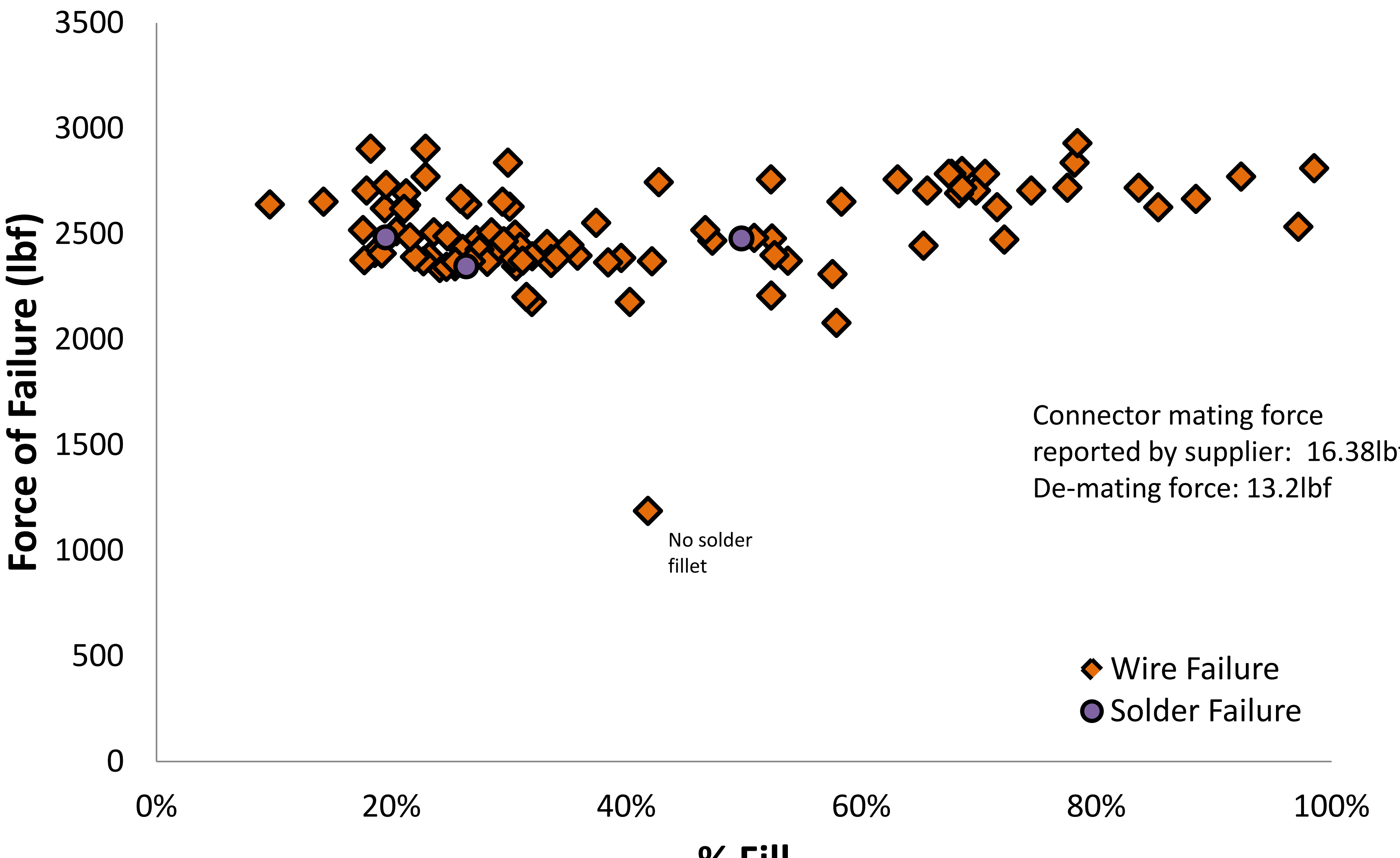


cPCI Wire Pull Testing

- Pull on pins soldered to board
- Axial stress on wire, shear stress on solder-to-wire connection
- Pull until:
  - Pin breaks
  - Solder connection breaks
- Record force when failure occurs
- How does breaking force relate to:
  - Shock event?
  - High-cycle fatigue event?
  - Mating/De-mating event?


Wire Pull Forces Related to Solder Fill Amounts - Per Pin
Force of Failure (lbf)
25
20
15
10
5
0
0%
20%
40%
60%
80%
100%
% Fill
Connector mating force reported by supplier: 16.38 lbf
No solder fillet present
Wire Failure
Solder Failure
Mating Force for one pin
Unmating Force for one pin

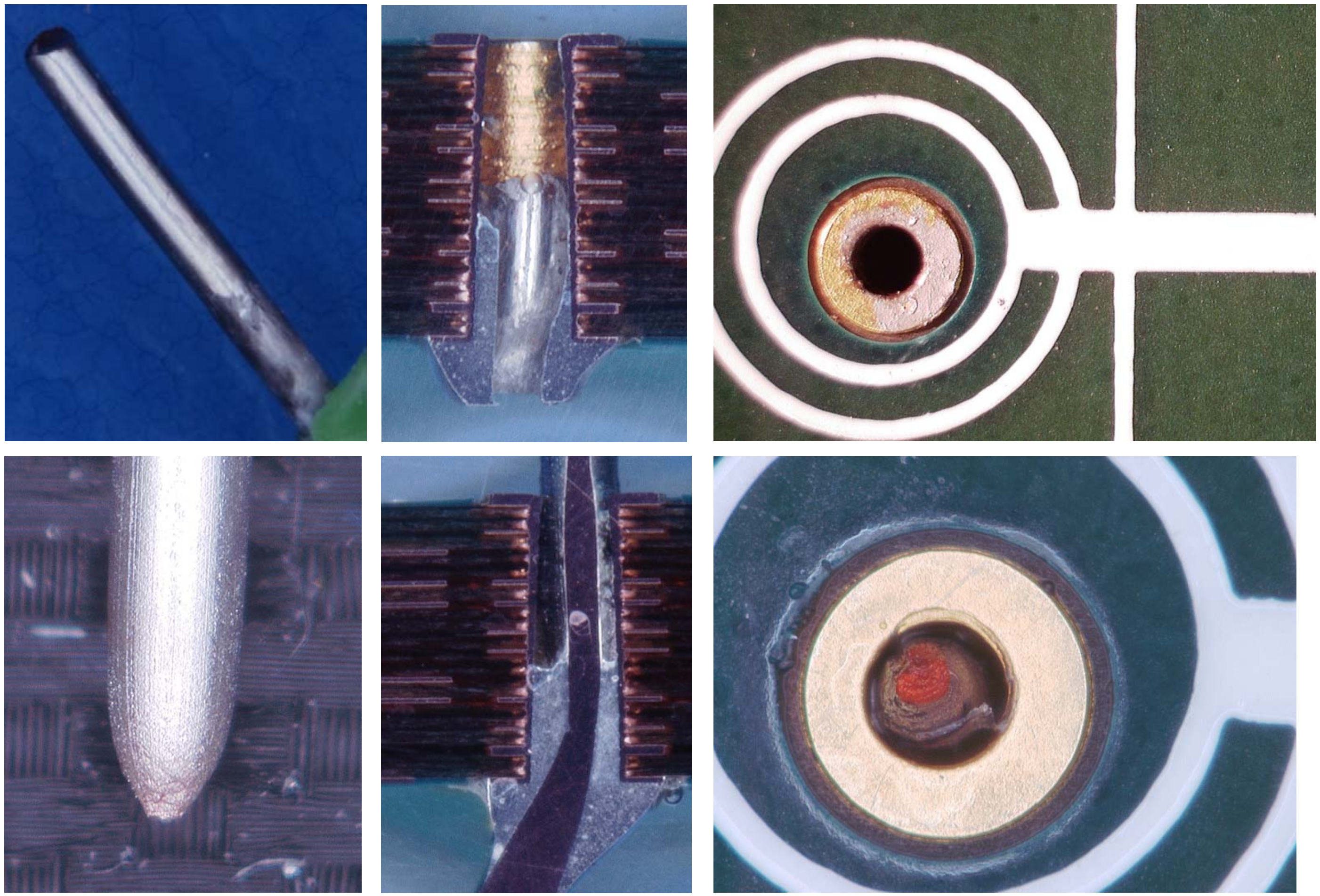
Results to Normalized to Connector



Wire Pull Failure Location
Cross Sections

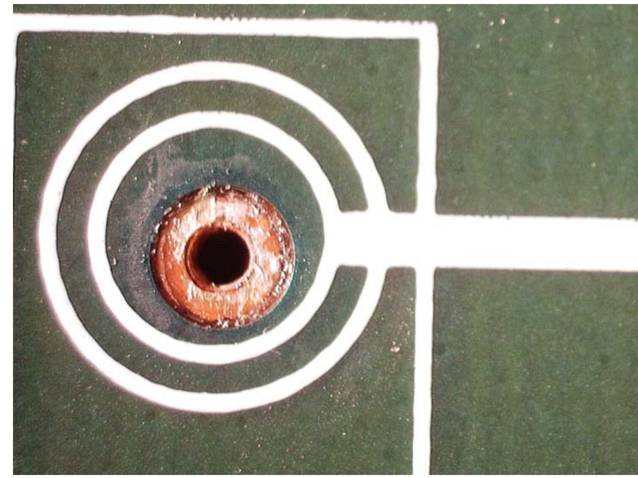
Solder

Pin

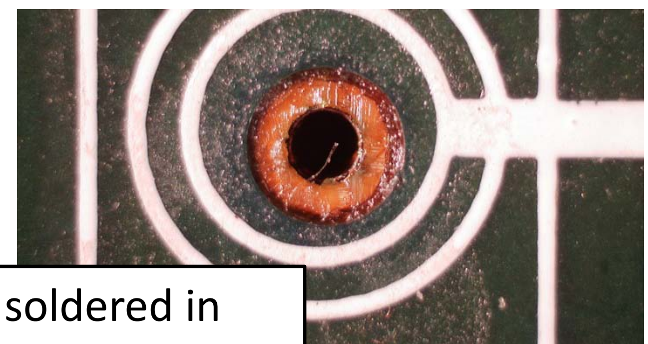


Wire Pull Failure Locations

Pad



PTH

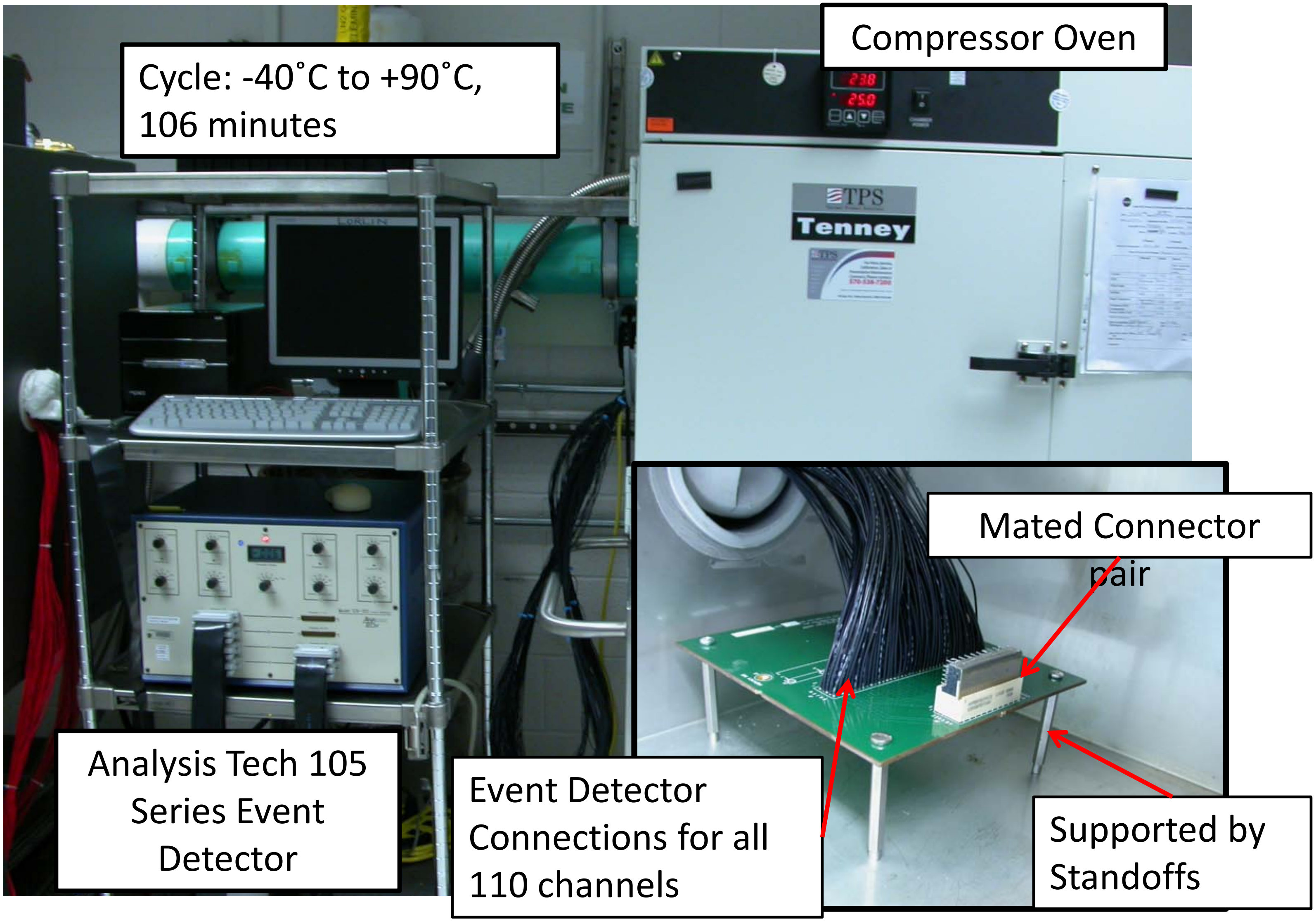


Note: These failures only seen when wires soldered in from the top of the board. – not relatable to cPCI connector solder joints as the connectors are soldered from the bottom.

Wire Pull Conclusions

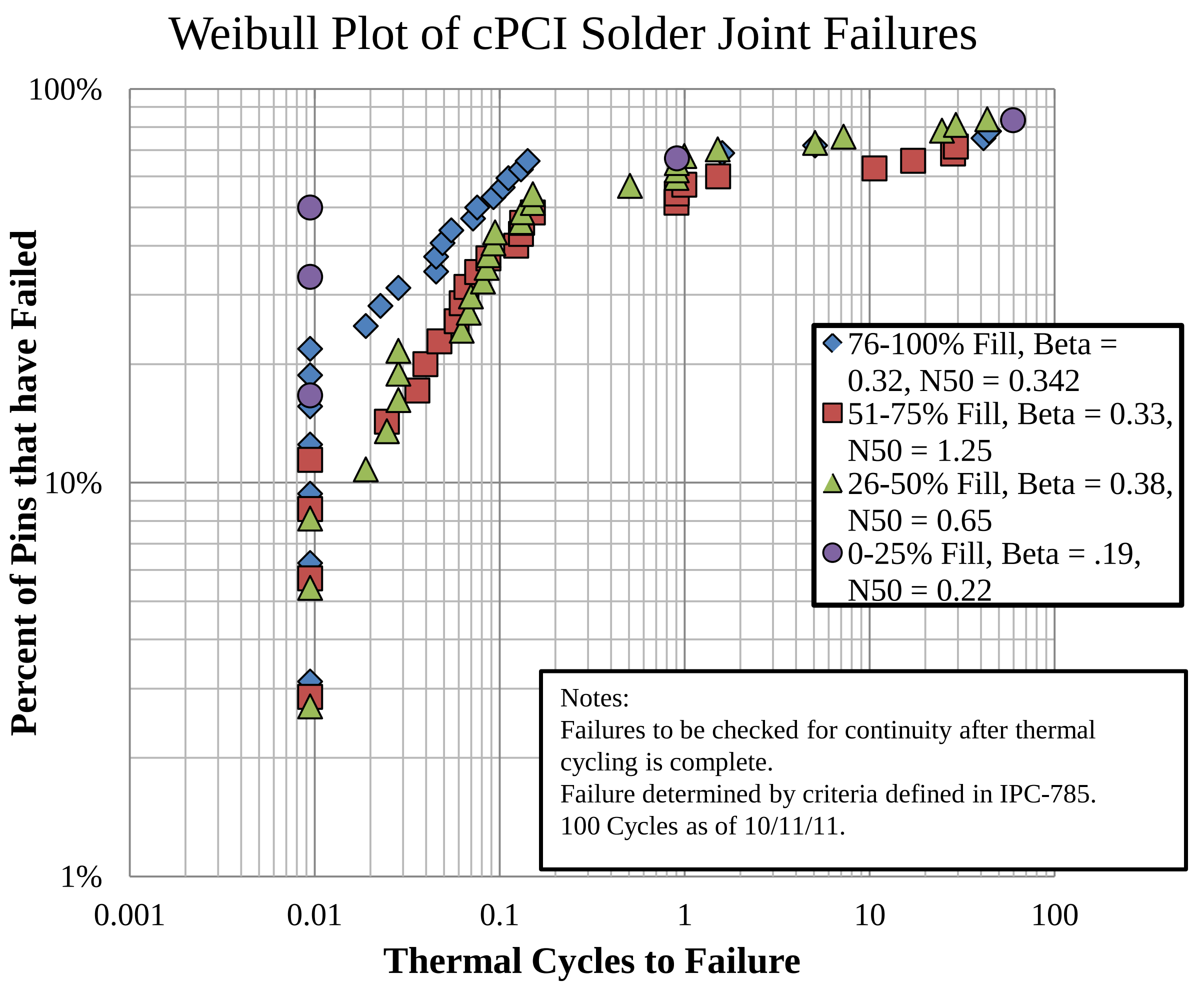
- Fully and partially filled through-hole solder joints are very strong.
- The number of joints in cPCI connectors provide high levels of tensile strength redundancy. If just two joints are filled 20% or higher, they will support mechanical overstresses.

Test Vehicle #2: Thermal Cycling



Thermal Cycling Summary

- Failures detected in all ranges of fill, scattered
- Recommend at least 800 cycles to collect more data
- Recommend a second test that includes coating, staking, and random vibration tests as preconditioning, and compare results
- Run same test at different temperatures for a larger database of failures



Future Work

- Finish and resolve thermal cycling testing and results.
- Study Reworked vs Original joint
- Round robin evaluation of X-ray inspection results
- Can Interconnect Stress Testing (IST) demonstrate through-hole joint reliability?

Acknowledgements

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Jeannette Plante
Marcellus Proctor
Denise Ratliff
Chris Reinking
Amir Sadeghi
Kusum Sahu
Nilesh Shah
Michael Solly
Ken Tran
Banks Walker
Richard Williams
Al Lookingland, Northrop Grumman